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Robust 9-QAM digital recovery for spectrum shaped coherent QPSK signal

Bo Huang,^{1,2,4,*} Junwen Zhang,^{3,4} Jianjun Yu,³ Ze Dong,⁴ Xinying Li,³ Haiyan Ou,² Nan Chi,³ and Wen Liu¹

¹Wuhan National Laboratory for Optoelectronics, School of Optoelectronics Science and Engineering, Huazhong University of Science and Technology, Wuhan, 430074, Hubei, China

²Department of Photonics Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark

³Department of Communication Science and Engineering, Fudan University, Shanghai 200433, China

⁴ZTE Corporation, Morristown, NJ 07960, USA

*yellowbo@gmail.com

Abstract: We propose 9-ary quadrature amplitude modulation (9-QAM) data recovery for polarization multiplexing-quadrature phase shift keying (PM-QPSK) signal in presence of strong filtering to approach Nyquist bandwidth. The decision-directed least radius distance (DD-LRD) algorithm for blind equalization is used for 9-QAM recovery and intersymbol interference (ISI) compression. It shows the robustness under strong filtering to recover 9-QAM signal rather than QPSK. We demonstrate 112 Gb/s spectrum shaped PM-QPSK signal by wavelength selective switch (WSS) in a 25-GHz channel spacing Nyquist wavelength division multiplexing (NWDW). The final equalized signal is detected by maximum likelihood sequence decision (MLSD) for data bit-error-ratio (BER) measurement. Optical signal-to-noise ratio (OSNR) tolerance is improved by 0.5 dB at a BER of 1×10^{-3} compared to constant modulus algorithm (CMA) plus post-filter algorithm.

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1. Introduction

Doubling spectral efficiency (SE) is an interesting and attractive topic. Nyquist pulse is generated to achieve the Nyquist limit of SE for a given baud rate [1, 2]. However, the operating rate is limited by the speed of digital/analog converter (DAC). Partial response system gives the same high SE at a cost of optical signal-to-noise ratio (OSNR) penalty due to its multilevel detection. Recently, quadrature duobinary (QDB) is proposed to approach SE of 4 bit/s/Hz [3–5]. A simpler and more realistic means is spectrum shaping based on the wavelength selective switch (WSS) [6–10]. A post-filter by receiver-side duobinary shaping is used in order to apply conventional digital signal processing (DSP) schemes.

Generally, the data sampled at the time of T , which is in the center of the symbol, will be recovered. But it suffers from severe intersymbol interference (ISI) under strong filtering. In this paper, we propose to recover the data sampled at the time of $T/2$, which is between adjacent symbols. It is found that this method has higher tolerance and robustness to the strong filtering. The constellation is 9-ary quadrature amplitude modulation (9-QAM) like for spectrum shaped QPSK signal. In that case, we design a set of processing algorithms to recover the 9-QAM signal. In previous work, blind radius-directed equalizer (RDE) followed by decision-directed least mean square (DD-LMS) was proposed [5]. However, the radius of the ideal center constellation point is zero for the 9-QAM signal. When the amplified spontaneous emission (ASE) noise is prior to phase noise, the phase information of center constellation point is indistinct because amplitude is close to zero. So DD-LMS algorithm, which is phase sensitive, is inaccurate for the final convergence to the 9-QAM signal.

The decision-directed least radius distance (DD-LRD) algorithm has been proposed for 16-QAM [11], which is phase independent. In this paper, DD-LRD is modified to fit in with 9-QAM constellation and used for blind equalization and ISI compression. We demonstrate 112 Gb/s spectrum shaped polarization multiplexing-quadrature phase shift keying (PM-QPSK) signal with a 25-GHz bandwidth WSS in the Nyquist wavelength division multiplexing (NWDM) channel. The final equalized signal is detected by maximum likelihood sequence detection (MLSD) [7] for data bit-error-ratio (BER) measurement.

2. Operation principle and simulation

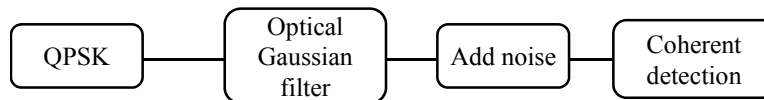


Fig. 1. Simulation model.

Figure 1 illustrates our simulation model. 28 Gbaud QPSK signal is generated by an in-phase/quadrature (I/Q) modulator. A following optical band-pass filter of 4th order Gaussian type is utilized to shape the spectrum of QPSK signal. The 3-dB filter bandwidth is emulated from 22 to 30 GHz in simulation, so that the spectrum is significantly compressed to approach Nyquist bandwidth. The ASE noise is added before optical homodyne coherent detection. The OSNR is 30 dB which is defined in a 0.1-nm noise bandwidth. We ignore the influence of carrier phase drift in the simulation. Continuous wave (CW) laser sources at the transmitter and for local oscillator (LO) at the coherent receiver are both of 0-Hz linewidth. The signal is finally sampled at twice the baud rate.

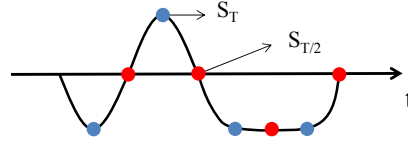


Fig. 2. Signal is sampled at the time of T (blue sample) and T/2 (red sample).

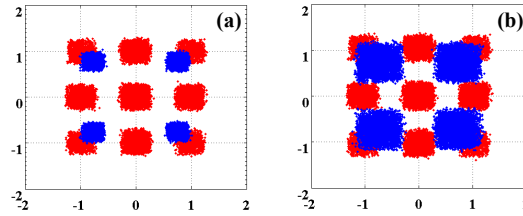


Fig. 3. Constellations of the sampled signals with the filter of (a) 28-GHz and (b) 24-GHz. The blue and red dots represent the signals sampled at the time of T and T/2 respectively.

The sampled signal is divided into two groups: one is the signal sampled at the time of T, i.e., the timing phase is 0, and the other is the signal sampled at the time of T/2, i.e., the timing phase is π offset. Figure 2 illustrates two groups of samples. We define T samples as S_T and T/2 samples as $S_{T/2}$. The constellations of the received signal with the optical Gaussian filter of 28 GHz and 24 GHz are shown in Fig. 3(a) and 3(b) respectively. We observe that T samples are like 4-QAM (blue dots) and T/2 samples are like 9-QAM (red dots). Obvious ISI occurs after 4th order Gaussian filter. We can see that each constellation point becomes square-like distribution. Comparing constellations of the sampled signals with 28- and 24-GHz filtering, T samples have much larger ISI (blue dots in Fig. 3(b)) when 24-GHz filter is applied, while the T/2 samples keep nearly unchanged (red dots in Fig. 3). In that case, we can recover the 9-QAM like $S_{T/2}$ samples instead of conventional processing to S_T samples in the presence of strong filtering. We expect the new concept of data recovery has better performance.

Assuming S_T is known, $S_{T/2}$ can be estimated approximately by linear interpolation which is expressed as Eq. (1),

$$S_{T/2} = \frac{S_T(k) + S_T(k+1)}{2} \quad (k=1, 2, 3, \dots) \quad (1)$$

It is quite interesting that $S_{T/2}$ is to a certain extent duobinary shaped signal which will share the nature of narrow bandwidth of the duobinary coded signal. Therefore T/2 samples have larger tight filtering tolerance and lower ISI thanks to the partial response system. However, a little higher OSNR is required since multilevel detection must be applied to the 9-QAM signal. The signal can be finally detected with MLSD algorithm which makes use of the inherent intersymbol memory and minimizes the number of error by selecting the most probable trellis path [6].

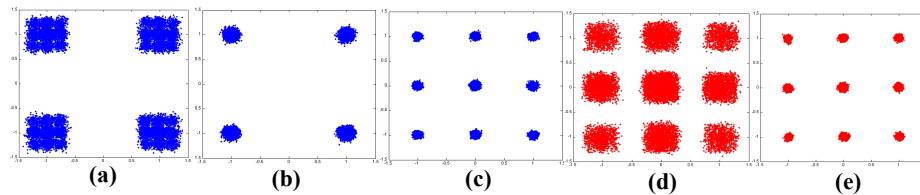


Fig. 4. Constellations of (a) T samples, (b) CMA processing, (c) CMA + post-filter processing, (d) T/2 samples, (e) DD-LRD processing.

In order to decrease the signal ISI, an adaptive 9-tap finite impulse response (FIR) filter can be applied. The constant modulus algorithm (CMA) is normally used to blindly update the FIR tap weights for the QPSK signal which has constant modulus. But CMA doesn't work well enough when big ISI exists. A post-filter with 2 taps (i.e. one symbol delay and add), which performs the function of duobinary shaping, is proposed in the references [6, 7] to further release strong filtering limitation. Figure 4(a) shows the T samples suffering from severe ISI. CMA (Fig. 4(b)) and post-filter (Fig. 4(c)) can reduce the ISI to a certain degree.

In our scheme, we propose to recover the 9-QAM T/2 samples directly. CMA is not well compatible for this signal because 9-QAM does not present constant symbol amplitude and error signal cannot approach to zero. We propose to use the DD-LRD algorithm, which is much more accurate than CMA, to update the filter tap weights. The error function is given by

$$e(n)=y(n)(|\hat{d}(n)|^2-|y(n)|^2) \quad (2)$$

Where $y(n)$ is the equalized signal, and $\hat{d}(n)$ is the decided symbol. And the filter tap weights updating function is given by Eq. (3),

$$w(n)=w(n-1)+\mu e(n)x(n)^* \quad (3)$$

Where $w(n)$ is the adaptive FIR filter, and μ is the convergence parameter. The DD-LRD has superior tolerance to ISI because of its phase independence manner. Besides, it has rapid convergence speed which is robust to time varying situation. Figure 4(d) shows the T/2 samples suffering from severe ISI. LRD algorithm presents excellent performance to restrain the ISI as shown in Fig. 4(e).

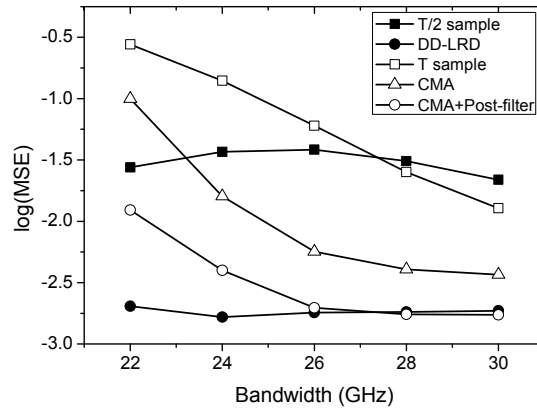


Fig. 5. Measured MSE of the signals after T and T/2 sampling, DD-LRD, CMA, and CMA + post-filter processing

Figure 5 shows measured mean squared error (MSE), which is defined as $\frac{1}{n} \sum_{i=1}^n (\hat{d}(i) - y(i))^2$, varying with different DSP algorithms. The hollow curves present the processing to T samples of the QPSK constellation. 1 dB MSE improvement is obtained using CMA compared to T sampling signal and further 0.5 dB is gained using post-filter with 26-GHz optical filtering. However tighter filter bandwidth below 26 GHz induces even more serious ISI. MSE degrades rapidly with narrower bandwidth and the benefit of ISI compression from CMA decreases to less than 0.5 dB when the filter bandwidth is 22 GHz. The solid curves present the processing to T/2 samples of the 9-QAM constellation. 1.4 dB MSE improvement is obtained using DD-LRD compared to T/2 sampling signal. It is found that the MSE changes very little as filter bandwidth varying from 22 to 30 GHz. The performance is quite comparable with larger than 28 GHz filtering between DD-LRD and CMA + post-filter

algorithms. So it is more robust to strong filtering to recover 9-QAM signal on $T/2$ samples than QPSK on T samples.

3. Experiment and discussion

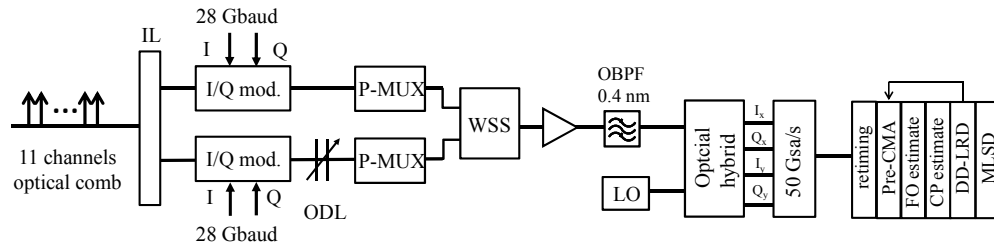


Fig. 6. Experimental setup. I/Q mod.: I/Q modulator, IL: interleaver, P-MUX: polarization multiplexer, WSS: wavelength selective switch, ODL: optical delay line, OBPF: optical band-pass filter, LO: local oscillator.

Figure 6 shows the experimental setup of 28 Gbaud NWDM PM-QPSK with WSS spectrum shaping. The NWDM subchannels are from a comb generator based on phase and intensity modulators with 25-GHz carrier spacing and equal tone power [10]. The odd and even channels are separated by using a 25/50 GHz optical IL. The 28 Gb/s binary electrical signals are generated from the two-channel pulse pattern generator (PPG) with a pseudo-random binary sequence (PRBS) length of $2^{11}-1$. The optical QPSK signals are generated using two I/Q modulators. The even and odd channels are individually polarization multiplexed with a differential delay of 150 symbols between two polarizations. After that, they are combined with 25-GHz channel spacing and the spectrum of each channel is shaped by a waveshaper (i.e., WSS). We measured the WSS with 3-dB bandwidth of 21.6 GHz, 10-dB bandwidth of 30 GHz, and 20-dB bandwidth of 37.1 GHz. At the receiver, one tunable optical band-pass filter (OBPF) with 3-dB bandwidth of 0.4 nm is employed to choose the measured subchannel. Polarization diversity homodyne detection is utilized at the receiver. The linewidth of external cavity lasers (ECLs) at the transmitter and for LO at the receiver are both smaller than 100 kHz. We apply 50-GSa/s Analog/Digital conversion (ADC) sampling in the oscilloscope. The received data is then offline digital processed by a computer.

The received signal is resampled to 4 times of the symbol rate in order to process the timing phase estimation with square timing method [12]. 2 samples/symbol is processed by cubic interpolation according to the right extracted clock. Four 17-tap $T/2$ -spaced adaptive butterfly FIR filters are applied for polarization demultiplexing. The filters' weights are first updated by CMA for pre-convergence. The final adaptation is switched to DD-LRD for precise feedback control. The adaptive FIR filter and DD-LRD simultaneously play an important role of reducing the ISI and interchannel crosstalk. The frequency offset estimation (FOE) is based on the fast Fourier transform (FFT) method [13] and carrier phase estimation (CPE) is based on blind phase search (BPS) algorithm [14]. Finally, the signal is detected by MLSD in use of intersymbol memory for data BER measurement. As a comparison, CMA plus post-filter scheme as well as MLSD detection in [6–9] is also evaluated.

The measured BERs based on different algorithms as a function of OSNR are shown in Fig. 7. The OSNR is measured in a 0.1-nm noise bandwidth. The data is only processed with CMA (without MLSD decision) has poor performance due to the severe ISI. The BER even cannot achieve 1×10^{-3} in our measurement. We can observe the obvious ISI noise in Fig. 8(a). The required OSNR for BER at 1×10^{-3} based on our proposed 9-QAM recovery algorithm is 18 dB. The OSNR tolerance is 0.5 dB better than using CMA plus post-filter. The improvement is also gained in the simulation as shown in Fig. 7. The constellations recovered from CMA + post-filter and 9-QAM methods are shown in Figs. 8(b) and 8(c), respectively.

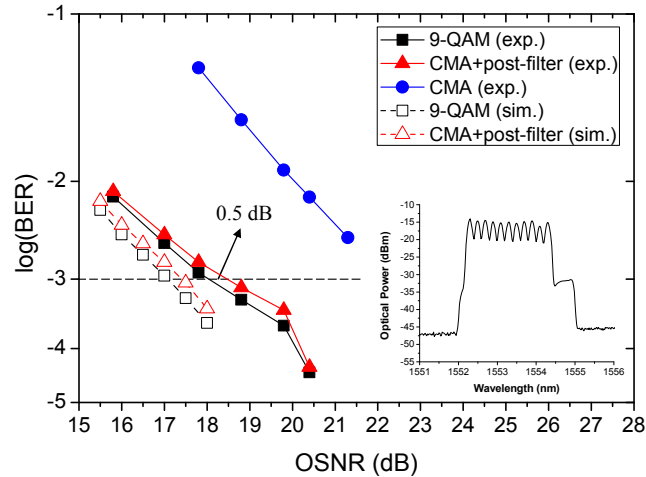


Fig. 7. Measured BER as a function of OSNR (0.1 nm). Inset is the spectrum of NWDW signal.

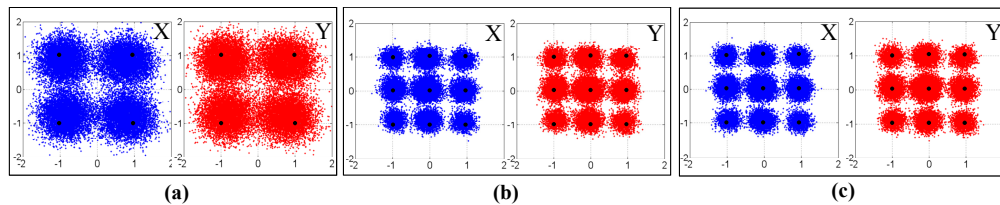


Fig. 8. Constellations of the recovered signal using the algorithm of (a) standard CMA, (b) CMA + post-filter, (c) proposed 9-QAM digital processing. The blue and red figures are X- and Y- polarization recovered data respectively.

Although 0.5 dB benefit is gained by applying our 9-QAM algorithm, this algorithm is more complex compared to CMA + post-filter algorithm because CMA + post-filter algorithm only needs additional 2-tap post-filter. For 9-QAM algorithm, carrier phase estimation is the major increased complexity, which is the same to 16-QAM. But it is believed that the complexity will be further reduced since more and more algorithms for 16-QAM are studied and proposed. In addition, robustness to strong filtering and superiorly rapid convergence speed make the 9-QAM digital recovery scheme more attractive and valuable for practical application.

4. Conclusion

We propose 9-QAM data recovery for PM-QPSK signal in the presence of strong filtering to achieve Nyquist bandwidth. The DD-LRD algorithm for blind equalization is used for 9-QAM recovery and ISI compression. It shows the robustness under strong filtering to recover 9-QAM signal rather than QPSK. We demonstrate 112 Gb/s spectrum shaped PM-QPSK signal by WSS in a 25-GHz channel spacing NWDW. The final equalized signal is detected by MLSD for data BER measurement. OSNR tolerance is improved by 0.5 dB at a BER of 1×10^{-3} compared to CMA plus post-filter algorithm.

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